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1.0 SCOPE

2.0 SCIENCE DEFINITION

2.1 WFIRST SCIENCE OBJECTIVES

WFIRST is a mission responding to the 2010 National Research Council New Worlds, New Horizons (NWNH) Astronomy and Astrophysics Decadal Survey top priority recommendation in the large space mission category. The science program for WFIRST includes two dedicated surveys to tackle outstanding questions in dark energy research and exoplanet exploration, and a substantial Guest Observer program to enable targeted investigations of astrophysical phenomena to advance other goals from the Decadal Survey.

2.1.1 **High Latitude Survey: Dark Energy and Broad Astrophysical Investigations**

In October 2011, the Nobel Prize in Physics was awarded “for the discovery of the accelerating expansion of the Universe through observations of distant supernovae.” The accelerating expansion of the universe is the most surprising cosmological discovery in many decades, with profound consequences for our understanding of fundamental physics and the mechanisms that govern the evolution of the cosmos. The NWNH recommendation calls for a mission to “settle fundamental questions about the nature of dark energy.” WFIRST will characterize the history of cosmic acceleration, with the goals of determining whether it is caused by a new energy component of the universe or by a breakdown of general relativity on cosmological scales, and whether the cause has been constant in time or evolving over the history of the universe. To accomplish this goal, both the history of cosmic acceleration and growth of structure will be characterized by multiple independent means.

The history of cosmic acceleration will be characterized by measurement of luminosity distance $D_L(z)$ through observations of type Ia supernovae (SNIa); measurements of angular diameter distance $D_A(z)$ and the Hubble parameter $H(z)$ through Baryon Acoustic Oscillations (BAO) in a galaxy redshift survey; and measurements of weak gravitational lensing (WL) of background galaxies by foreground matter in a galaxy imaging survey. In order to provide good systematics control and cross-checks between the techniques, WFIRST seeks to measure the spectra, light curve, fluxes, and redshifts of 2000 Type Ia supernovae over the redshift range of $z = 0.2$ to 1.7 in the supernova survey, the positions and redshifts of 20 million emission line galaxies in the redshift range of $z = 1 – 2$ in the galaxy redshift survey, and the shapes and redshifts of 500 million galaxies in the redshift range of $z = 0 – 2$ in the weak lensing imaging survey.

The growth of structure and the evolution of galaxies on a wide variety of scales, ranging from cosmological scales and high redshift to the local group will be characterized from weak lensing measurements and independently by means of redshift space distortions (RSD) in the galaxy redshift survey. The evolution of galaxies and quasars at high redshifts will be studied by means of multi-band imaging to characterize the number density, luminosity, and colors as a function of redshift. At intermediate redshifts, the growth of structure will be characterized by means of strong and weak gravitational lensing by galaxy clusters. In the local universe, the history of galaxy assembly will be studied by imaging studies of tidal tails of dwarf galaxies surrounding larger galaxies in the local group, and by kinematic studies of tidal streams around the Milky Way.

Primary science objectives 1-2 below support the goal for the Dark Energy program:

Objective 1: Measure the expansion history of the Universe with sub-percent precision over the redshift range z = 0 to 2, by combining three or more measurement techniques (BAO, SNIa and WL) to provide coverage and independent metrics across the full redshift range.

Objective 2: Measure growth of structure with sub-percent precision over the redshift range z = 0 to 2 combining at least 2 techniques (WL and RSD) to provide coverage and independent metrics across the full redshift range.

2.1.2 **Exoplanet Survey**

The discovery of planetary companions to Sun-like stars was, along with the discovery of dark energy, one of the greatest breakthroughs in modern astronomy. These discoveries have excited the astronomical community and the broader public as well. Since then, the pace of exoplanet discovery has increased each year. There are now well over 1000 confirmed exoplanets and Kepler has identified thousands of candidates that await confirmation. Nature has surprised astronomers with the enormous and unexpected diversity of exoplanetary systems, containing planets with physical properties and orbital architectures that are radically different from our own Solar System. Since the very first discoveries, we have struggled to understand this diversity of exoplanets, and in particular how our solar system fits into this menagerie.

WFIRST will advance our understanding of exoplanets along two complementary fronts: the statistical approach of determining the demographics of exoplanetary systems over broad regions of parameter space by gravitational microlensing and the detailed approach of characterizing the properties of a sample of nearby exoplanets by means of high-contrast imaging and spectroscopy. These two complementary surveys will provide a comprehensive view of the formation, evolution, and physical properties of planetary systems. In addition, information and experience gained from both surveys will lay the foundation for, and take the first steps toward, the discovery and characterization of a “pale blue dot” — a habitable Earth-like planet orbiting a nearby star.

The goal of the WFIRST exoplanet microlensing survey is to understand how planetary systems form and evolve and to determine the makeup of the cold, outer regions of planetary systems. To accomplish this goal, the WFIRST microlensing survey seeks to monitor a large number of systems for exoplanets, providing a yield for reasonable assumptions about planet frequency of at least 3000 planets with mass above 0.1 Earth masses and semi-major axes greater than 1 AU, with at least 10% of these planets having the mass of the Earth or less. WFIRST also seeks to derive host star masses for at least half of the detected planetary systems. Following Kepler, the crucial next step is to assay the population of planets in the cold, outer regions of planetary systems, and to determine the frequency of free-floating planets. These two populations of planets are invisible to Kepler, yet constitute the two other main reservoirs of planets predicted by theories. WFIRST is uniquely capable of detecting planets with mass as small as the mass of Mars or below in significant numbers. Since Mars-mass bodies are thought to be the upper limit to the rapid growth of planetary “embryos”, determining the planetary mass function down to a tenth the mass of the Earth uniquely addresses a pressing problem in understanding the formation of terrestrial-type planets. WFIRST will extend the search for free-floating planets down to the mass of Earth and below, a task not possible with other techniques and not possible from the ground. This will allow it to address the question of whether ejection of planets from young systems is a phenomenon associated only with giant planet formation or also involves terrestrial planets.

Primary science objective 3 below supports the goal for the Exoplanet Microlensing program:

Objective 3: Complete the statistical census of planetary systems in the Galaxy, from the outer habitable zone to free floating planets, including analogs to all of the planets in our Solar System with the mass of Mars or greater.

The next Objective is motivated by our need to understand the structure, atmospheres, and evolution of a diverse set of exoplanets. This is an important step toward the larger goal of assessing the characteristics of Earth-like planets that may be later discovered in the habitable zones of nearby stars. It is unlikely that any such planets will have exactly the same size, mass, or atmosphere as our own Earth. A large sample of characterized systems with a range of properties will be necessary to understand which properties permit habitability and to properly interpret these discoveries.

The goal of the WFIRST exoplanet direct-imaging survey is to understand the compositions and atmospheric constituents of a variety of planets around nearby stars and to determine the properties of debris disks around nearby stars in order to understand how planets interact with these debris disks. To accomplish this goal, the direct-imaging survey seeks to characterize photometrically at least a dozen known radial velocity planets, of at least 4 Earth radii with minimum star-planet separations of TBD, characterize spectroscopically half of these, and search for other planets around nearby (~10 pc) stars. Additionally, WFIRST aims to search for low surface density circumstellar disks around several dozen nearby stars as well as image the inner regions of known bright disks. This direct imaging survey of planets orbiting nearby stellar systems offers a critical approach to studying the detailed properties of exoplanets complementary to the transit studies of the Kepler mission. First, as with microlensing, planets detected by direct imaging tend to be at longer orbital periods than those found by transits. Second, spectra of directly imaged planets provide powerful diagnostic information about the structure and composition of the atmospheres. Similarly, high-contrast imaging of debris disks around nearby stars will provide crucial insights into the processes governing planet formation. Broadband imaging of such disks will provide information on the amount, location, and composition of circumstellar dust.

Primary science objective 4 below supports the goal for the Exoplanet Direct Imaging program:

Objective 4: Discover new planets and disks around nearby stars and characterize these new and previously known planets and disks by means of high-contrast imaging and spectroscopy and develop coronagraph technology to enable this science and as an investment for future missions.

2.1.3 **Guest Observer Science**

With the spatial resolution of Hubble's powerful Wide Field Camera 3 infrared channel and more than 200 times its field of view, WFIRST will enable astronomers to make important contributions towards many of the enduring questions listed in the Decadal Survey. Consistent with the recommendation from the Decadal Survey, WFIRST will have a robust Guest Observer program for wide-ranging astrophysical investigations using the wide field and coronagraph instruments. This program will allow WFIRST be able to observe targets across the full sky and at a flexible cadence throughout each year of the mission lifetime. The program will allow for interruptions due to target of opportunity investigations to open up a new window on time-domain phenomena. Specific scientific studies in the Guest Observer program will be selected through a peer-review process similar to those in use by the current Great Observatories. All observatory capabilities, such as the wide field of view imager, slit and slitless spectrographs, and coronagraph, will be available to the community for Guest Observer programs. Each of these will open new areas of discovery space. A substantial fraction of the mission lifetime will be devoted to these targeted observations.

Objective 5: A substantial fraction of the WFIRST mission lifetime will be dedicated to a peer-reviewed Guest Observer program. This program will allow for a broad range of scientific studies of astrophysical targets in our Galaxy and external galaxies, to be observed over the full sky and at an adequate frequency through each year of the mission lifetime.

2.2 SCIENCE INSTRUMENT SUMMARY DESCRIPTION

The WFIRST payload features a telescope with a 2.4-meter aperture and on-axis secondary mirror, which feeds two different instrument volumes containing the wide field instrument and the coronagraph technology demonstration instrument. The telescope hardware was built by ITT/Exelis under contract to another agency and was provided to NASA. The telescope is a 2.4-meter, obscured two-mirror system. Repurposing modifications will include conversion to a three-mirror anastigmat (TMA) optical configuration to enable a wide field-of-view instrument, and replacements for hardware that was not provided to NASA.

The wide-field instrument includes two channels, a wide-field channel and an integral field unit (IFU) spectrograph channel. The wide-field channel uses a filter/grism wheel to provide an imaging mode covering 0.76 – 2.0 μm and a spectroscopy mode covering 1.35 – 1.95 μm. The wide-field focal plane uses 4k x 4k HgCdTe detectors with 10 μm pixels. The HgCdTe detectors are arranged in a 6x3 array, providing an active area of 0.281 deg^2 at a plate scale of 0.11 arcseconds per pixel. The IFU channel uses an image slicer and spectrograph to provide individual spectra of each 0.15 arcsec wide slice covering the 0.6 – 2.0 μm spectral range over a 3.00 x 3.15 arcsec field at a plate scale of 0.075 arcseconds per pixel.

The coronagraph is an instrument to advance the key technologies required to enable a future direct imaging and spectroscopic instrument capable of detecting and characterizing Earth-like planets while accomplishing the scientific objectives specified in 2.1.2. The coronagraph includes imaging and spectroscopy modes, and a low order wavefront sensor to perform exoplanet detection and characterization. The coronagraph covers a spectral range of 0.4 – 1.0 μm, providing a contrast of 10^{-9} with an inner working angle of 3λ/D at 400 nm.

3.0 PROJECT DEFINITION

3.1 PROJECT ORGANIZATION MANAGEMENT

3.2 PROJECT ACQUISITION STRATEGY

4.0 MISSION REQUIREMENTS

All requirements are to be verified pre-launch and in-orbit.

4.1 BASELINE MISSION REQUIREMENTS

The WFIRST baseline mission is defined as the nominal operation of the WFIRST observatory (in the configuration specified at the time of Confirmation) for a nominal period of 6.25 years. This includes two phases, the in-orbit checkout (IOC) and the baseline science mission. The IOC phase represents the period during which the observatory is activated and brought to a state of nominal science operations and is expected to be 3 months in duration. The baseline science mission is defined as the period of time during which the WFIRST baseline science observing plan is executed; during this phase, the full set of mission science objectives (Section 2.1) are to be addressed, and the baseline mission science requirements (specified in Section 4.1.1) shall be accomplished. Although there are scientific objectives and baseline and threshold requirements tied to the Exoplanet Direct Imaging program, as a technology demonstration instrument the coronagraph shall not drive the overall mission requirements.

4.1.1 **Baseline Mission Science Requirements**

Achievement of the baseline science mission objectives (See Section 2.1) imposes the following baseline mission scientific requirements (BSRs) on the mission.

BSR1: WFIRST Wide-Field Instrument (WFI) shall measure positions and redshifts of emission-line galaxies in the redshift range z = 1 - 2 with a position accuracy of TBD and a redshift accuracy of 1 part in 1000 and a minimum detectable point-source line flux of 0.5x10^-16 ergs/cm^2/s at 7σ significance.

BSR2: WFIRST WFI shall measure shapes of galaxies at z=0-2 in at least 2 bands and fluxes in at least 4 bands for photometric redshifts with photometric accuracy of TBD and with shape measurement systematics contributing less than 0.1% uncertainty to the cosmic shear signal.

BSR3: WFIRST WFI shall measure the spectra, light curve, fluxes, and redshifts of Type Ia supernovae with 5 day cadence over a redshift range of z = 0.2 to 1.7 with observational errors and calibration uncertainties that keep the aggregate precision of the data set better than 0.2% in distance.

BSR4: WFIRST WFI shall measure the light curve and fluxes of microlensing events in the galactic bulge region to detect planets as low as 0.1 Earth masses at separations down to 1 AU.

BSR5: WFIRST WFI shall measure the masses of at least TBD% of the microlensing planet host stars to a precision of at least 20%.

BSR6: WFIRST Coronagraph shall directly image exoplanets around nearby stars, and carry out color photometry measurements in the spectral range about 400-1000 nm, for planets as small as 4 Earth radii.

BSR7: WFIRST Coronagraph shall spectroscopically characterize planets by measuring continua and spectral absorption features over the wavelength range from about 600 – 950 nm with resolution about 70.

BSR8: WFIRST shall be capable of detecting a disk with 10 times our solar system's zodiacal flux in or near the habitable zone (~1 AU) of a solar-type star at a distance of 8 pc at 450 nm.

4.1.2 **Baseline Mission Technical Requirements**

In order to address the baseline science objectives described in Section 2.1 and satisfy the corresponding baseline mission science requirements specified in Section 4.1.1, the WFIRST mission shall meet the following baseline technical requirements (BTRs).

BTR1: The WFIRST observatory and associated ground support system shall be designed and fabricated to sustain science operations for at least 6.25 years.

BTR2: The WFIRST observatory shall employ an existing telescope with a 2.36 m diameter primary mirror, on-axis secondary mirror, and associated metering structure.

BTR3: The WFIRST observatory shall be diffraction limited at 1.2 micrometers defined as having a Strehl Ratio greater than or equal to 0.8 across the wide field instrument field of view.

BTR4: The observatory shall orbit the Earth in a 28.5 deg inclined geosynchronous orbit.

BTR5: The observatory shall have the capability to respond to Target of Opportunity request to point at a transient object in the sky within the Field of Regard of the observatory

BTR6: The WFIRST wide field instrument shall have a minimum field of view of 0.25 deg^2.

4.1.3 **Baseline Mission Data Requirements**

In order to address the baseline science objectives described in Section 2 and satisfy the corresponding baseline mission science requirements specified in Section 4.1.1, the WFIRST mission shall meet the following baseline mission data requirements (BDRs):

BDR1: Data completeness and data delivery type requirements

BDR2:

BDR3:

BDR4:

4.2 THRESHOLD MISSION REQUIREMENTS

The WFIRST threshold mission is defined as the nominal operation of the WFIRST observatory (in the actual launch configuration) for a period of 6.25 years (the same as the baseline mission), including a commissioning phase. The commissioning phase represents the period during which the observatory is activated and brought to a state of nominal science operations and is expected to be 3 months in duration. The threshold science mission is defined as the period of time during which the WFIRST threshold science observing plan is executed; during this phase, the mission science objectives (specified in Section 2.1) are to be addressed, but only the threshold mission science requirements (specified in Section 4.2.1) need to be accomplished.

4.2.1 **Threshold Mission Science Requirements**

This section defines the science requirements imposed on WFIRST for the threshold mission science objectives, as specified in Section 2.1.

Achievement of the threshold science objectives imposes the following threshold science requirements on the mission.

TSR1:

TSR2:

TSR3:

TSR4:

4.2.2 **Threshold Mission Technical Requirements**

In order to address the threshold science requirements described in Section 4.2.1, the WFIRST mission shall meet the following threshold technical requirements (TTRs).

TTR1:

TTR2:

TTR3:

TTR4:

4.2.3 **Threshold Mission Data Requirements**

In order to address the threshold science objectives described in Section 2 and satisfy the corresponding threshold mission science requirements specified in Section 4.2.1, the WFIRST mission shall meet the following threshold mission data requirements (TDRs):

TDR1:

TDR2:

TDR3:

TDR4:

4.3 MISSION PERFORMANCE REQUIREMENTS

4.4 MISSION SUCCESS CRITERIA

The following are the criterion for WFIRST mission success:

Measure the history of cosmic acceleration and the growth of structure with a precision sufficient to differentiate between a new energy component and a breakdown of General Relativity on cosmological scales.

Determine the statistical population of planets with the mass of Earth and above in the cold, outer regions of planetary systems to test theories of planetary formation and evolution.

5.0 NASA MISSION COST REQUIREMENTS

5.1 COST CAP

5.2 COST MANAGEMENT AND SCOPE REDUCTION

6.0 MULTI-MISSION FACILITIES

The WFIRST project shall use the following NASA facilities:

7.0 EXTERNAL AGREEMENTS

The following agreement with non-U.S. entities will be required to carry out the WFIRST project:

8.0 EDUCATION AND PUBLIC OUTREACH (E&PO)

9.0 SPECIAL INDEPENDENT EVALUATION

10.0 WAIVERS

Waivers against 7120.5 E are shown below.

11.0 ACRONYM LIST

12.0 APPROVALS

13.0 CONCURRENCE

14.0 NPR 7120.5 COMPLIANCE MATRIX